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A new installation (THETIS) for thermal-hydraulic tests of forced-flow superconducting cables used in fusion technology, such as e.g. Cable-in-Conduit Conductors (CICCs), has been prepared at West Pomeranian University of Technology, Szczecin. The installation enables pressure drop measurements using water at room temperature in short samples of conductors in a wide range of Reynolds number. We present the new installation and demonstrate its capabilities by reporting the results of the first hydraulic test conducted on a reference sample (JT-60SA TF conductor). Further development of THETIS is foreseen to make possible measurements of heat transfer coefficients in superconducting cables.

Keywords: pressure drop, friction factor, superconducting cables

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1. Introduction

Current models used for thermal–hydraulic analyses of forced-flow superconducting cables used in fusion technology are typically 1-D and they require reliable predictive correlations for the transverse mass-, momentum- and energy transport processes occurring between different cable components, in order to assess any fusion magnet design in both normal and off-normal operating conditions [1]. The void fraction of some Nb_3Sn superconducting cables designed for the DEMO Toroidal Field coil is strongly reduced (down to about 20%) [2]. Conductors with such low void fractions have never been tested for pressure drop yet. Moreover, it was observed [2], that discrepancies between predictions of different bundle friction factor correlations available in literature [3-5] strongly increase with decreasing the void fraction. There is a need of experimental verification of the accuracy of the existing predictive friction factor correlations at very low void fractions. The situation with heat transfer phenomena in a CICC bundle is even less satisfactory. Only a few heat transfer correlations for flow in a CICC bundle have been proposed in literature [6-8], but none of them is widely accepted for predictive purposes. As a result, in thermal-hydraulic analyses of conductors designed for the DEMO coils [1,9-13] classical heat transfer correlations for flows in smooth tubes are used, which are definitely over-conservative in this case. Systematic measurements of heat transfer coefficients in a CICC bundle should be performed which could serve as a base for further attempts to develop a predictive correlation.

To reliably assess the predictive capability of an existing bundle friction factor correlation, or to develop a new one, it is beneficial to have experimental data measured in a possibly wide range of Reynolds number (Re). Friction factor data can be derived from pressure drop measurements using different fluids, e.g. water [14-18] or nitrogen [19,20] at room temperature (RT), or helium at room or cryogenic temperatures [5,17,18,

21-23]. The largest Re range can be reached when the same sample is tested with water and another, less viscous, fluid [17,18], however it would be desirable to have experimental data covering the whole considered Re range. Systematic experimental studies of pressure drop in CICCs with different void fractions and cable layouts, using water at RT, were conducted in EPFL-CRPP [6-10], however in these experiments the maximum pressure at the sample inlet was 10 bar, which limited the maximum Re which could have been reached, particularly for conductors with low void fractions.

A new installation (THETIS) for thermal-hydraulic tests of forced-flow superconducting cables used in fusion technology, such as e.g. CICCs, is being prepared at West Pomeranian University of Technology, Szczecin. The first stage of its construction has been completed. The aim of the paper is to present THETIS and demonstrate its capabilities by reporting the results of the first performed hydraulic test.

2. Experimental setup

2.1 THETIS installation

At the present stage the THETIS installation enables pressure drop tests of short conductor samples using distillated water at room temperature. The photo of the installation and its hydraulic scheme is presented in Figs. 1 and 2. The pressure head up to 25 bar in the installation is induced by a progressive cavity pump (BELLIN LZ 500L/KW) with variable speed operation. The mass flow rate in the circuit is adjusted by changing the rotational speed of the pump in the range 10 to 60 Hz. Two bypasses of the pump with different diameters enable precise adjustment of small mass flow rates by suitable opening of two throttle valves (VT-1 and VT-2 in Fig.2). The tolerable range of the water temperature in the pump is 10-50ºC. A conductor sample is attached to the installation using flexible hoses with flange connections,

Table 1. Specification of the instrumentation used in THETIS

Measuring instrument	Type	Measured quantity	Measuring range	Basic measurement uncertainty
Flow meter	KROHNE OPTIMASS 1000	$\dot{m}$	20 - 3000 kg/h	± 0.15% of measured value
Temperature sensor 1 and 2	T-111-6-115-60-3-G1/2-NA-A-Pt 1000-400	T_1, T_2	-200 – 400 ° C	± 0.15 ºC ± 0.2% of |measured value|
Pressure sensor 1	Aplisens PR-28/0-25BAR/M20x1.5	p_1	0 – 2.5 MPa	± 0.2% of measuring range

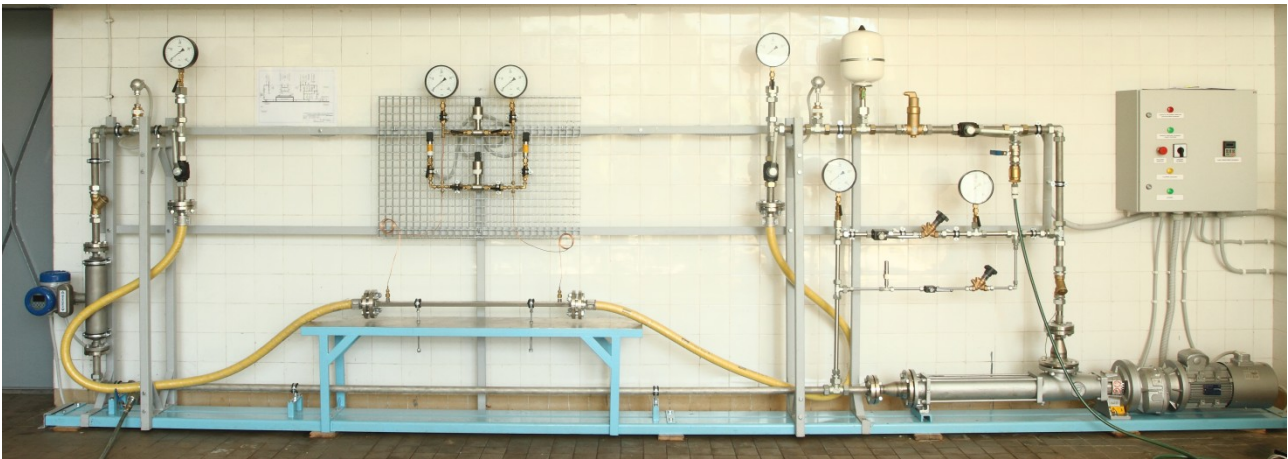|				
Pressure sensor 2	Aplisens PR-28/0-10BAR/M20x1.5	p_2	0 -1 MPa	± 0.2% of measuring range
Differential pressure sensor 1	Aplisens APR-2000PD/0-250KPA/P/M20 x1.5	Δp_1	0 – 0.25 MPa	± 0.1% of measuring range
Differential pressure sensor 2	Aplisens APR-2000PD/0-16 BAR/P/M20x1.5	Δp_2	0 – 1.6 MPa	± 0.1% of measuring range
Data Acquisition System	APAR AR207	-	-	± 0.1% of measuring range

Fig. 1. Photo of the THETIS installation.
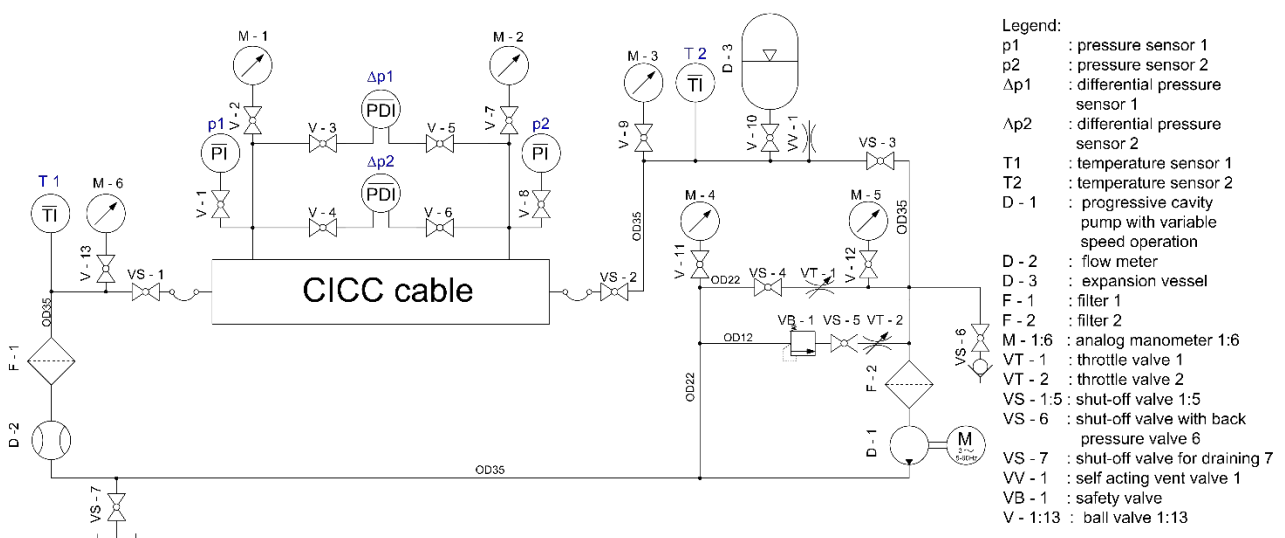
Fig. 2. Hydraulic scheme of the installation

is attached to the installation using flexible hoses with flange connections, which allows to vary the sample length in the range of about 0.5 to 2 m. The applied measuring instrumentation (see Table 1) and the automatic data acquisition system enable accurate and convenient measurements.

2.2 Reference sample

A reference sample used for the first pressure drop test performed with THETIS was the JT60-SA TF single channel CICC. Full characteristics of this conductor is given in [20, 24], whereas the conductor parameters relevant for the present study are recalled in Table 2. Fig. 3 shows the photo of the sample connected to THETIS.

Table 2. Characteristics of the JT-60SA TF sample [20]

Description	Symbol	Unit	Value
Void fraction	φ	%	32
Flow area	A_f	mm^2	125.8
Hydraulic diameter	D_h	mm	0.454
Distance between pressure taps	L	m	0.865

Fig. 3. Photo of the JT-60SA TF sample.

3. Test results and discussion

The mass flow rate in the circuit was increased stepwise and readings of the sensors listed in Table 1 were registered every 1 s. The average values and their standard deviations were calculated for the data collected during steady states. To assess pressure drop in the sample, readings of the pressure sensors p_1 and p_2 were used in the range $\Delta p > 1.6$ MPa, whereas the more accurate differential pressure sensors Δp_2 and Δp_1 were used in the range 0.25 MPa $< \Delta p_2 < 1.6$ MPa and $\Delta p_1 < 0.25$ MPa, respectively. The overlap between Δp values measured with different sensors was in good agreement within the range of uncertainties and confirmed the good accuracy of their calibration. The longitudinal Darcy friction factor (f) and the Reynolds number were deduced from measurements of pressure drop and mass flow rate ($\dot{m}$), according to the formulas:

$$f = \left(2 D_h \rho A_f^2 \Delta p\right) / \left(\dot{m}^2 L\right),$$
(1)

$$\mathrm{Re} = \left(\dot{m} D_h\right) / \left(\mu A_f\right),$$
(2)

where the water density (ρ) and dynamic viscosity (μ) were calculated at the reference conditions: $p_{ref} = (p_1 + p_2)/2$ and $T_{ref} = (T_1 + T_2)/2$. The combined uncertainties of the friction factor and Re were calculated as [25]:

$$u(f) = f \sqrt{\left[\frac{u(\Delta p)}{\Delta p}\right]^2 + 2\left[\frac{u(\dot{m})}{\dot{m}}\right]^2 + \left[\frac{u(L)}{L}\right]^2},$$
(3)

$$u(\mathrm{Re}) = \left(u(\dot{m}) D_h\right) / \left(\mu A_f\right).$$
(4)

The results of the performed test in the dimensionless form (f vs. Re) are presented in Fig. 4. Over seventy JT-60SA TF short samples, cut from different conductor unit lengths provided by manufactures, were tested for pressure drop in the OTHELLO test facility using nitrogen at RT [20]. Although the design of all these conductors was identical a noticeable scattering of the pressure drop test results was reported in [20]. The test results of two samples with the maximum and minimum friction factor, obtained in this experimental campaign have been added in Fig. 4. For the sake of comparison we have also included in Fig. 4 predictions of different friction factor correlations taken from literature [3-5].
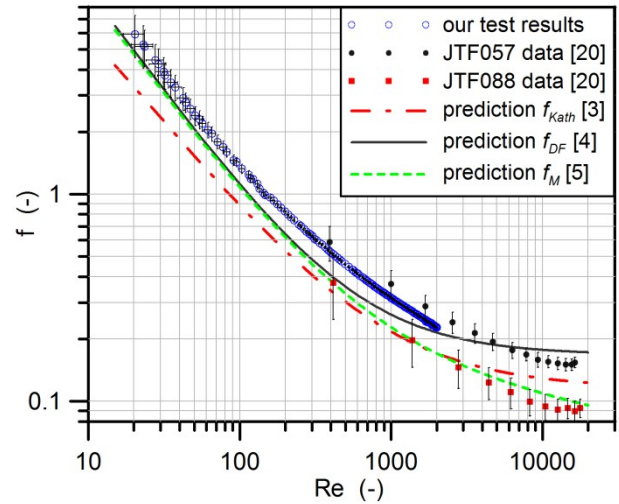

Fig. 4. Comparison of our test results with predictions of the friction factor correlations taken from literature [3-5] and with the extreme results of pressure drop test of similar samples performed at the OTHELLO test facility [20].

It is seen in Fig. 4 that our test results are consistent with the results of tests of similar samples performed at the OTHELLO test facility [20] and with predictions of friction factor correlations [3-5] used in thermal-hydraulic analyses of the DEMO TF coils [1,9-12]. The Re range achievable at THETIS and OTHELLO partially overlap. In the common Re range (400 - 2000) the accuracy of our measurements is better than that of OTHELLO. Both installations can be considered as complementary, and allow together to achieve a very wide Re range necessary for reliable

experimental verification of the existing friction factor correlations for conductors with very low void fraction.

4. Summary, conclusions and perspectives

The new THETIS installation for thermal-hydraulic tests of forced flow cooled superconducting cables using water at RT is being prepared at the West Pomeranian University of Technology, Szczecin. At the present stage THETIS enables convenient and accurate pressure drop tests of short conductor samples. The performed pressure drop test of the reference sample (JT-60SA TF CICC) demonstrated that the Re range achievable in THETIS is complementary to that of the OTHELLO test facility. Further development of THETIS is foreseen, e.g. adding several temperature sensors as well as a heater at the sample inlet and a cooler at the pump inlet, to make possible measurements of heat transfer coefficients in superconducting cables. External teams are invited to send us conductor samples to be tested, on a collaborative basis.

Acknowledgments

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